WHITE PAPER-V.1

Parameters and design issues of

Electron Cooler for Low-Energy RHIC program

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The goal of this document is to initialize progress towards design of Electron Cooler for cooling of heavy ion in RHIC at energies below nominal injection energy. This is a working document and material will be replaced on continues bases. Most numbers are preliminary and will be corrected as design proceeds. This is not a design document and intended for discussion purpose only.

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1 OVERVIEW

Recently, a strong interest emerged in running the Relativistic Heavy Ion Collider (RHIC) at low beam total energies of 2.5-25 GeV/nucleon [1-3], substantially lower than the nominal beam total energy of 100 GeV/nucleon. Collisions in this low energy range are motivated by one of the key questions of quantum chromodynamics (QCD) about the existence and location of critical point on the QCD phase diagram [4].

RHIC data will complement existing fixed-target data from AGS and SPS. In this energy range an energy scan will be conducted over about 7 different energies. There are several challenges to the operation of RHIC at such low energies. To evaluate the severity of these challenges and make projections for low-energy operation there have been several short test runs during RHIC operations in 2006, 2007 and 2008. Results of these test runs are summarized in Refs. [5].

Examples of stores at intermediate energy point with γ=4.9 are shown in Figs. 1.1. During the latest test run in March 2008 the lifetime was improved with the help of changes to defocusing sextupole configuration. The store length was extended from 15 minutes in 2007 to 1 hour in 2008.

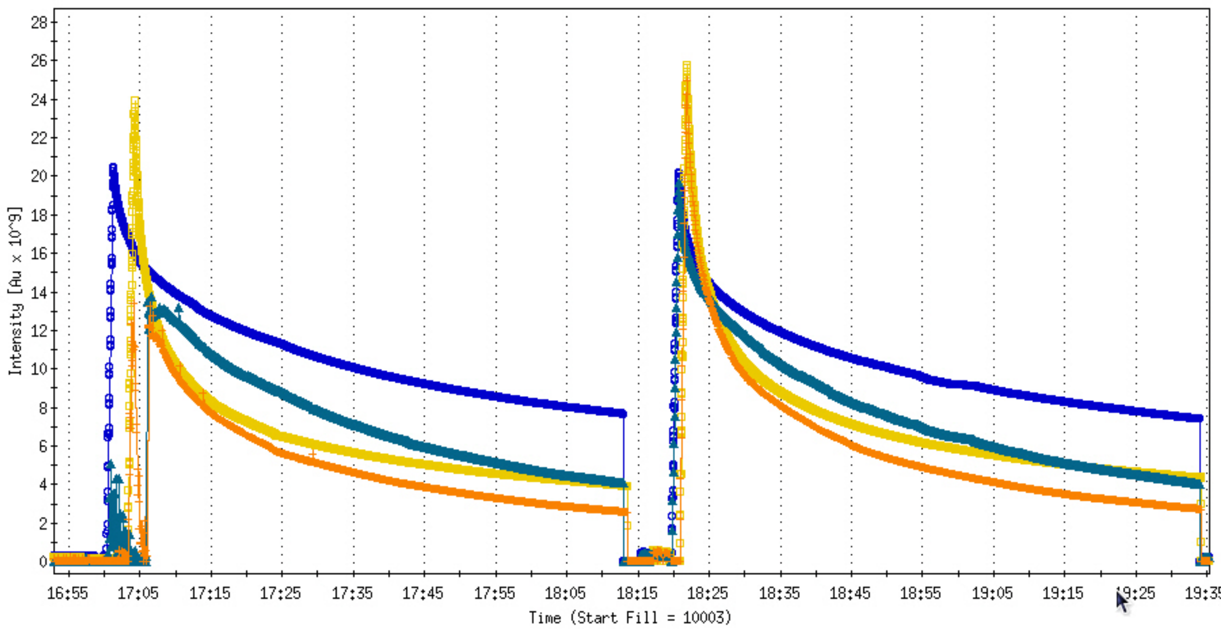

Fig. 1.1. Typical two stores during March 11, 2008 test run with Au at γ=4.9. 1) Blue ring: upper blue curve – total DCCT signal; lower light blue curve – bunched beam intensity with WCM. 2) Yellow ring: upper yellow curve – total DCCT signal; lower orange curve – bunched beam intensity with WCM.

For the test run in March 2008, the injected longitudinal emittance of gold ion bunches was close to the RF bucket acceptance. As a result, one can see significant loss from the RF bucket (lower light blue curve for Blue ring and orange curve for Yellow ring) driven by longitudinal IBS in Fig. 1.1. The total RF voltage was 430kV and 500kV for the Blue and Yellow rings, respectively.

The first improvement in luminosity should come from improvement of lifetime due to nonlinearities. In addition, both transverse and longitudinal IBS growth can be compensated by electron cooling technique [6]. Unfortunately, the ultimate limitation due to space charge prohibits strong cooling at the lowest energy points, which would give an otherwise dramatic increase in the luminosity.

$\sqrt{s_{NN}}$ GeV (center of mass energy)	5	6.3	7.6	8.8	12.3
γ	2.7	3.7	4.1	4.7	6.6
Estimated rate of useful events, Hz	0.55	1.0	3.0	3.0	15
Days needs to accumulate 5M events +setup	140+5	75+4	38+3	26+2	5
Expected improvement factor from cooling	3	3	3	4-5	6

Table 1.1 Estimates based on an assumption of useful events at γ=4.9.

Applying electron cooling directly in RHIC will increase the average integrated luminosity significantly, and will provide long stores for physics. With electron cooling it seems feasible to have at least a factor of 3-6 improvement in average luminosity depending on the energy. For luminosity with cooling we expect that improvement will be limited due to the space-charge effects. We have started APEX experiment at RHIC with main goal to understand whether we can operate with space-charge tune shift $\Delta Q>0.05$ under collisions, which would provide an additional luminosity improvement with electron cooling, compared to the estimates given above.

Note that a limited factor of 3 improvement from electron cooling for lowest energy points in Table 1.1 is driven by an assumption of space-charge limit [7] and assumes that machine performance will be substantially improved without cooling (no strong intensity drop in the first few minutes, as can be seen in Fig. 1.1). If, however, significant fast initial intensity drop remains, then space-charge limit is relaxed, and electron cooling can provide additional factors of improvements on top of the factor of 3 given in Table 1.1 due to a possibility of cooling ion beam emittance with a subsequent reduction of beta function at the Interaction Point.

In addition, if signatures of the Critical Point are found, it is expected that a request for high statistics, for example 50M events, will follow. Electron cooling in RHIC enables acquisition of such statistics in a reasonable period of time. Without electron cooling, acquisition of high statistics of about 50M events is impractical.

2 ELECTRON COOLER PARAMETERS

Luminosity improvement is needed mostly for low ion c.m. energies of 5-12 GeV/nucleon. This requires electron beam with a kinetic energy range of 0.86-2.8MeV. It turns out that with a present setup of two RHIC detectors and RF tuning limits, simultaneous operation of both detectors is not possible at some energy points without significant modifications [8]. On the other hand, use of cooling to improve luminosity in the c.m. energy range of 5-8.6 GeV/nucleon, where both detectors can operate simultaneously and where most luminosity improvement is needed, requires only a 0.86-1.8MeV cooler. As a result, the electron cooler should be able to operate at least up to 1.8MeV kinetic energy.

Although several schemes for electron cooler for required energy range were considered, the path with the fewest unresolved issues was chosen. Our present baseline cooler design is based on existing FNAL's Recycler Pelletron [9-17], which is presently operating at 4.36MeV. This 6MeV Pelletron in principle should be able to provide cooling of ions all the way up to the present RHIC injection energy. This will require operation of Pelletron up to 4.9MeV, which seems feasible since high-current operation is not required.

2.1 Pelletron

Pelletron is the electrostatic (Van de Graff-type) accelerator which uses a chain of charge carrying pellets rather than a typical Van de Graaff belt to carry charge to the terminal. The chain of pellets exhibits wear characteristics that are more favorable than those of conventional belts and ensure cleaner, more stable operation over the long term. The Pelletron used in FNAL Recycler electron cooler was built by National Electrostatic Corporation. The machine is enclosed in a steel tank that conforms to the American Society of Mechanical Engineers standards; it has a large bolted flange on top through which the accelerator is assembled.

The FNAL Pelletron is a 6MV machine which allows stable operation with high current at 4.3 MeV kinetic electron energy. If only small currents are required, it may allow stable operation at higher energy. The machine is a vertical dual-column structure about 3.5 meters in diameter and 8 meters tall. The machine uses sulfur-hexafluoride (SF6) gas to adequately insulate the high voltage terminal. The insulating properties of the gas are enhanced by pressurizing the gas to around 6-7 atmospheres (see Appendix for more details). Pelletron schematics is shown in Fig. 2.1, while photo of existing FNAL Pelletron is shown in Fig. 2.2.

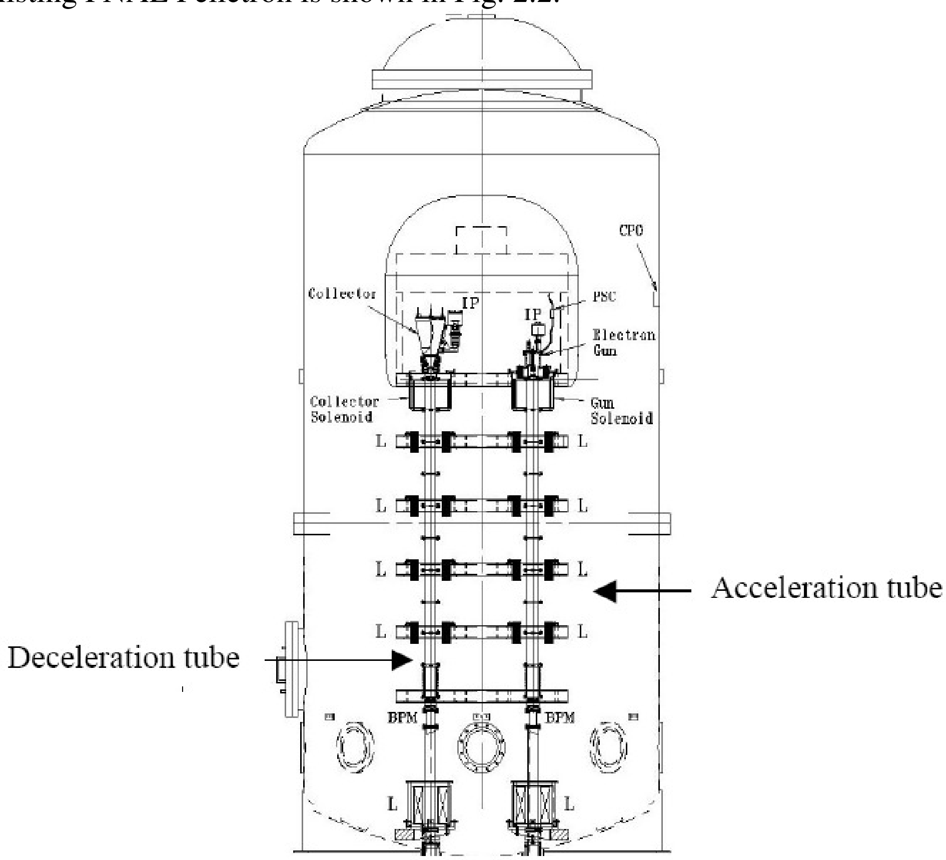

Fig. 2.1 Schematics of Pelletron electrostatic accelerator (courtesy of FNAL).

Fig. 2.2 Picture of FNAL Recycler cooler Pelletron (courtesy of FNAL).

2.2 Electron beam parameters

At low energy, RHIC ion bunches are very long with the full bunch length up to 30 nsec. DC electron beam is ideally suited for cooling of such long ion bunches. To counteract IBS for lowest energy point only 0.05A of DC current is required. To provide also additional cooling of beam emittance for higher energy points requires electron beam current of about 0.1A.

Depending on beam energy and longitudinal emittance, the ion beam will have rms longitudinal momentum spread in the range of σ_p=4-6×10^{-4}. This sets a limit on the rms momentum spread of electron beam of < 4×10^{-4}. Present relative rms energy spread in Recycler's electron beam is about 1×10^{-4} which satisfies this requirement.

The requirement on transverse angles of electron beam in the cooling section is given by the angular spread of the ion beam. For example, for rms normalized emittance of 2.5 mm-mrad at γ=2.7, and 30 m beta function in the cooling section, the ion beam rms angular spread in the lab frame is 0.18 mrad. This results in a requirement to have transverse angular spread of electrons in the cooling section < 0.2 mrad. Since the ion bunch angular spread decreases with energy increase, even stricter control of electron angular spread will be needed at higher energy points to maintain cooling performance. Thus a careful consideration of various effects and estimate of full "angular budget" similar to what was done at FNAL will be needed for the full energy range of interest.

Some basic parameters of the cooler are summarized in Table 2.1. Electron beam requirements shown in Table 2.1 are given only for the lowest energy points of interest since cooling requirement at energies above 2.8MeV is not yet fully established. The value in brackets indicates the maximum possible energy of Pelletron-based cooler operation discussed here.

Table 2.1: Basic parameters of electron beam.

Electron kinetic energies, MeV	0.86-2.8 (4.9)
DC current, mA	50-100
Length of cooling section per ring, m	10
RMS momentum spread	<0.0004
RMS transverse angles, mrad	<0.2
Undulator magnetic field, G	3
Undulator period, cm	8

Table 2.1 lists parameters of undulator which allows to suppress loss of heavy ion on recombination with electron beam. However, it appears that without suppression of recombination resulting loss in integrated luminosity is not very severe. Thus, careful consideration of the use of undulators will be done during design stage before making them part of the cooler baseline.

2.3 Cooling approach

In low-energy electron coolers a magnetic field is required to provide transport of the electron beam. For energies of 0.9MeV and higher needed for our project, continuous magnetic field transport is no longer required.

However, in the cooling section, the interaction of the ion and electron beams results in ion beam loss due to recombination. Employment of strong magnetic field in the cooling section allows one to incorporate a large transverse temperature of the electron beam for recombination suppression. On the other hand, suppression of ion recombination can be achieved with rather weak undulator field in the cooling section still allowing non-magnetized beam transport. Since non-magnetized cooling significantly simplifies electron beam transport and reduces the cost of the cooler, it was chosen as our baseline approach.

The most straightforward approach is to use the Recycler's cooling section "as is", where control of angular spread is accomplished by 2m long weak solenoids. Here small magnetization at the cathode is required, which is the present Recycler's cooler approach. Due to the relatively small required current, another approach with zero magnetic field on the cathode and thus no magnetic field in the cooling section is also feasible. In the latter case, only short corrector solenoids every 2m will be needed to provide needed focusing in the cooling section. This latter approach would correspond to a pure case of "non-magnetized" cooling. Experimental investigation of this approach is highly desired. Such an experiment can be conducted at existing Recyler's cooler at FNAL. Both approaches to the cooling section will be carefully considered during design.

The use of undulators for recombination suppression in the cooling section is compatible with both approaches to the cooling section described above. However, the effect of undulators on cooling as well as engineering design should be carefully evaluated. For example, use of undulators together with present Recycler's cooler 2m long solenoids results in additional drift velocities of electrons. For baseline parameters, additional contribution to angular spread due to such drift was found to be within specifications. Regardless of the chosen approach, it appears that use of undulators may require significant engineering modification of the cooling section while the expected benefit in luminosity with recombination suppression seems rather modest. A careful cost-benefit consideration will be done before including undulators in the baseline.

3 ELECTRON BEAM TRANSPORT

The DC electron beam is generated by a thermionic cathode gun located in the high-voltage (HV) terminal of the electrostatic accelerator called Pelletron. After the beam is accelerated in Pelletron to required energy it is bent into beam transport line and transported to cooling sections in RHIC. After two cooling sections (one in Yellow and one in Blue rings), electron beam is turned around and brought back to Pelletron.

Presently we assume that we will use most of electron beam transport from FNAL Recycler, including all associated hardware. However, to adopt it to RHIC, additional turns in electron beam lines will be needed. Since electron beam needs to go in the same direction as the beam of heavy ions which should be cooled, electron beam will need to go around ion beam line in Blue ring first, then overlap with ions in Yellow ring over 10 meters, turn around to overlap with ions in Blue ring and return back to the Pelletron, which is located outside of RHIC tunnel. This is shown schematically in Fig. 3.1.

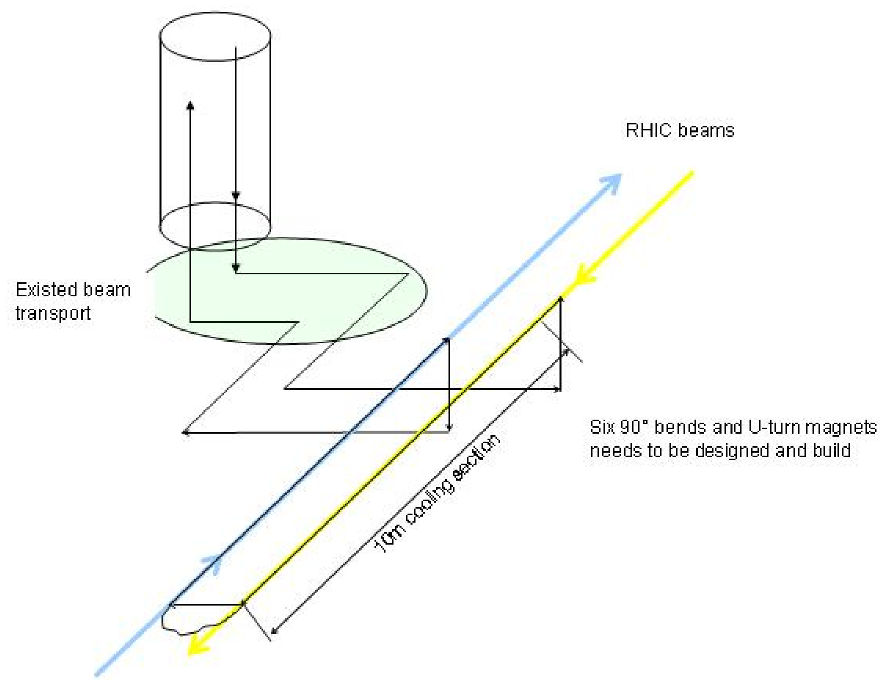

Fig. 3.1 Schematic representation of electron beam transport in RHIC tunnel.

This additional beam transport will require several additional magnets. Preliminary parameter for the magnets are:

Number=12: 45° dipoles, Gap 8 cm, n=0.5, maximum field 400 Gauss; R=50 cm, Lm=39.27 cm

Number=2: 90° dipoles, Gap 8 cm, n=0.5, maximum field 910 Gauss; R=16.73 cm, Lm=31.66 cm

Number=12: Solenoids ID 8 cm, maximum field 1.3 kGauss, L=20cm

Number=1: Quadrupole ID 8 cm L=10 cm maximum gradient 150 Gauss/cm (also needs to be checked with Fermi lab dispersion killer quadrupole parameters)

Here $n=-R/B*dB/dR$ is the gradient field,
where R is the radius of trajectory and B is a driving magnetic field in dipole. And both dipole magnets type are sector-type magnets.

Each 90° turn consists of two 45° dipoles and two solenoids (doublet).

180° turn around (U-turn) between cooling section consists of two 90° dipoles and a quadrupole.

An important feature of beam transport is that magnets should provide stable operation in full range of electron beam energies: 0.9-5 MeV. Presently Recycler cooler beam transport is designed for stable operation at only one electron beam energy of 4.3 MeV. Thus, careful examination should be done, to make sure that existing magnets and feedbacks are satisfactory even for lowest energy of operation in RHIC.

Power supplies:

Additional transport magnets will require the following power supplies:

45 degree dipoles: per magnet P=50W, I=5A, V=10V; each two dipoles can be put in series

90 degree dipoles: per magnet P=163W, I=36A, V=4.5V, two dipoles can be put in series

Quad: P=41W, I=5A, V=8V

Solenoids: P=68W, I=5A, V=14V; each two solenoids can be put in series

Requirement on power supplies precision is 100ppm. In addition, dipole power supplies will require feedback system to provide required stability, especially for operation at lowest energies (low fields).

4 COOLING SECTION

The cooling section is the region where the electron beam and ion beam overlap to produce cooling. The electron beam cools ions in RHIC Yellow ring then it is turned around and cools ions in RHIC Blue ring before going back to Pelletron (Fig. 3.1). The electron beam must maintain its good quality all the way through the second cooling section in Blue ring.

The Blue and Yellow ring cooling sections are about 10 meters each. For recombination suppression, the cooling section may need to be covered by helical undulators. Some space is taken up by closely spaced steering dipoles and beam position monitors used to keep the electron beam and ion beam in close relative alignment. Two approaches to the cooling section are described below:

1) The most straightforward approach is to use the Recycler's cooling section "as is", where control of angular spread is accomplished by 1.88m long weak (about 105G) solenoids. These long solenoids are separated by short 8cm gap for instrumentation. To help compensate for end effects through the instrumentation gaps between each solenoid, end coil solenoids are used at each end of the cooling solenoid. In this approach with finite magnetic field in cooling section small magnetization at the cathode is also required, which is the existing approach in Recycler's cooler.

2) On the other hand, due to a relatively small electron beam current, another approach with no magnetic field on the cathode and thus no magnetic field in the cooling section is also feasible. In the latter case, only short solenoids every 2m will be powered to provide required focusing in the cooling section. An experimental confirmation of such purely "non-magnetized" approach can be performed at FNAL and is highly desired.

If we adopt approach 1) with solenoids then present 5" beam pipe will need to be replaced by a smaller beam pipe. One cannot make beam pipe too small because of the dynamic aperture limitation in RHIC. On the other hand, beam pipe diameter should be small enough for baking of the vacuum chamber installed inside the solenoids.

If we adopt approach 2) then we do not need to use FNAL's cooling section solenoids and can leave present 5'' RHIC pipe unchanged. However, in such a case several potential problems like ion clearing should be resolved.

Vacuum system

The vacuum system of Recycler's cooling section is made up of independent vacuum sections with section length corresponding to each solenoid module, to simplify installation. Each vacuum section is approximately 2 meters in length and consists of a round beam pipe, bellows, beam position monitor, and instrumentation cross. The beam pipe diameter is 2".

For RHIC, radius of ion beam at low energies is significant which requires beam pipe of larger diameter in the cooling section. RHIC lattice in cooling section is not yet chosen, but with the beta functions of about 20 meters one gets sufficient rms beam size for long beam lifetime for the beam pipe diameter of 3". For nominal emittance of 15 μm (95%, normalized) this provides 8.3 rms beam sizes in 3.75cm pipe radius for the lowest energy, where beam size is the largest.

For an approach with magnetic field in cooling section, requirement of new vacuum beam pipe with larger diameter (3" or larger) compared to the one used at Recycler cooler (2"), requires careful checking that all essential devices (BPM's, correctors, etc.) can be still inserted between the vacuum chamber radius R=3.75cm and the inner board of solenoids with R=6.9cm.

For an approach without magnetic field in cooling section, new vacuum chamber is not needed and only minimum adjustments of RHIC lattice will be needed.

Magnetic shielding

To keep transverse angles of electron beam at acceptable level magnetic shielding of residual external magnetic field is required. At Recycler cooler this shielding provided by three concentric cylindrical layers of high initial permeability alloy. The resulting total attenuation for DC fields is about factor of 3000.

The lowest energy point for RHIC, assuming correctors every 2 meters, requires shielding of magnetic fields to about 2.5mG. This corresponds to attenuation factor of 200 assuming unshielded fields of 0.5G. To summarize, present Recycler's cooler shielding is adequate for RHIC as well.

5 RHIC LATTICE

RHIC lattice will need to be designed to have an appropriate ion beta-functions in the cooling section. Presently the beta functions are about 100 meters in proposed location of electron cooler (near IP4).

Approach with the solenoids in the cooling section (see Section 4) will require small beam size and thus smaller beta-function of about 20-30 meters in the cooling section in order to minimize impact of technical modifications of the cooling section. If necessary, additional quadrupoles can be considered to obtain smaller beta-functions in the cooling section.

Approach with zero magnetic field in the cooling section (see Section 4) will allow to keep present beam pipe size unchanged and beta-function values close to present.

6 LOCATION IN RHIC TUNNEL

As a starting point for discussions, location of electron cooler is "warm section" at 4'clock, with Pelletron blockhouse located on the outside of RHIC ring, was proposed. In the future, it is planned to move 197MHz RF cavities to the same warm section. They will be placed towards Q4 since it allows one to have maximum spacing between the beam pipes. The space between beam centerlines varies linearly over about 34 meter Q3-Q4 distance from 20.52" at Q3 to 30.34" at Q4 (~7.4mrad). Thus, remaining space for cooling section and turn around of electron beam is about 14 meters towards Q3. With 10m long cooling section, we will need to turn around electron beam at 12m distance from Q3. Distance between beam centers at this U-turn location is thus 60cm.

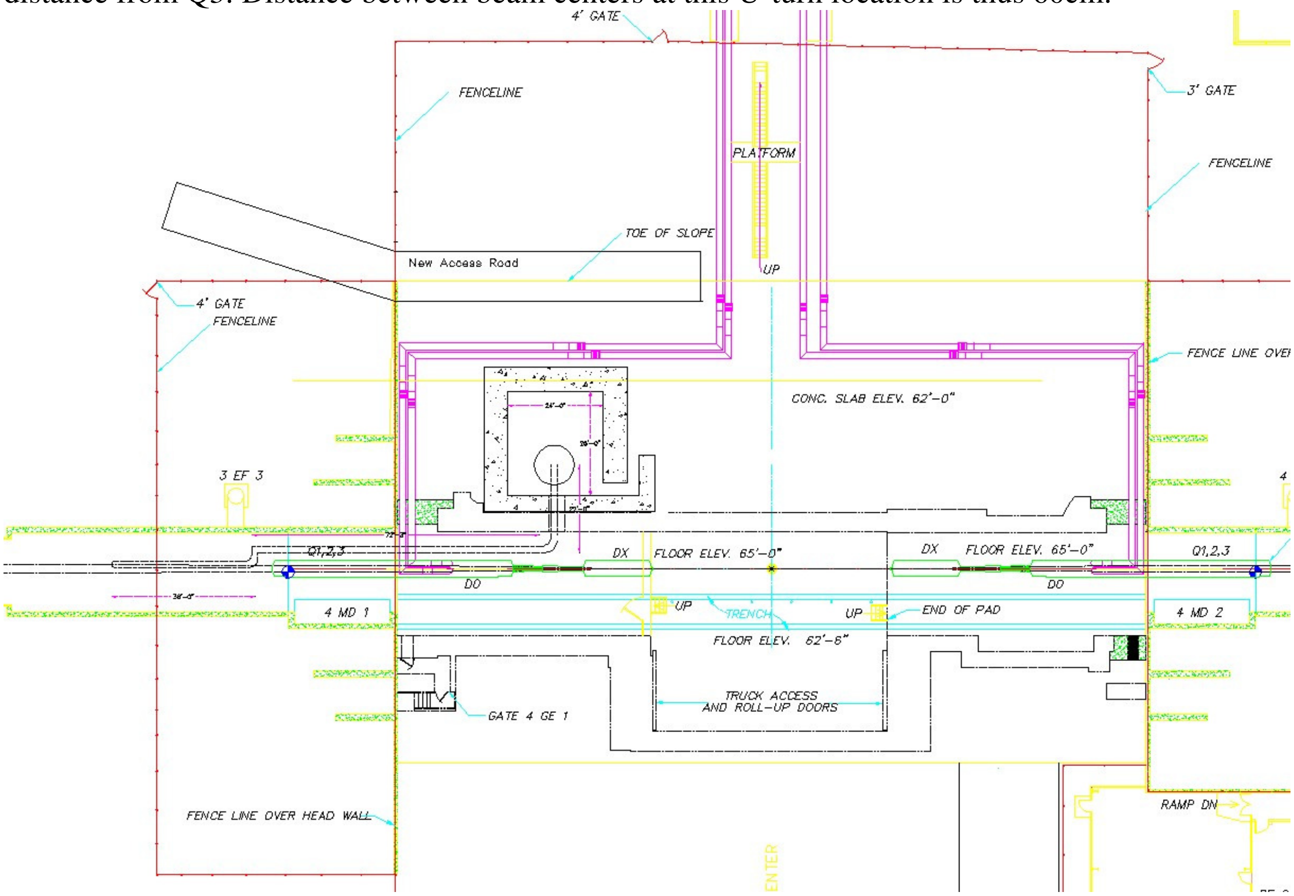

Fig. 6.1 Location at 4'clock in RHIC. Pelletron will be placed inside blockhouse (shown in black) located outside of RHIC tunnel.

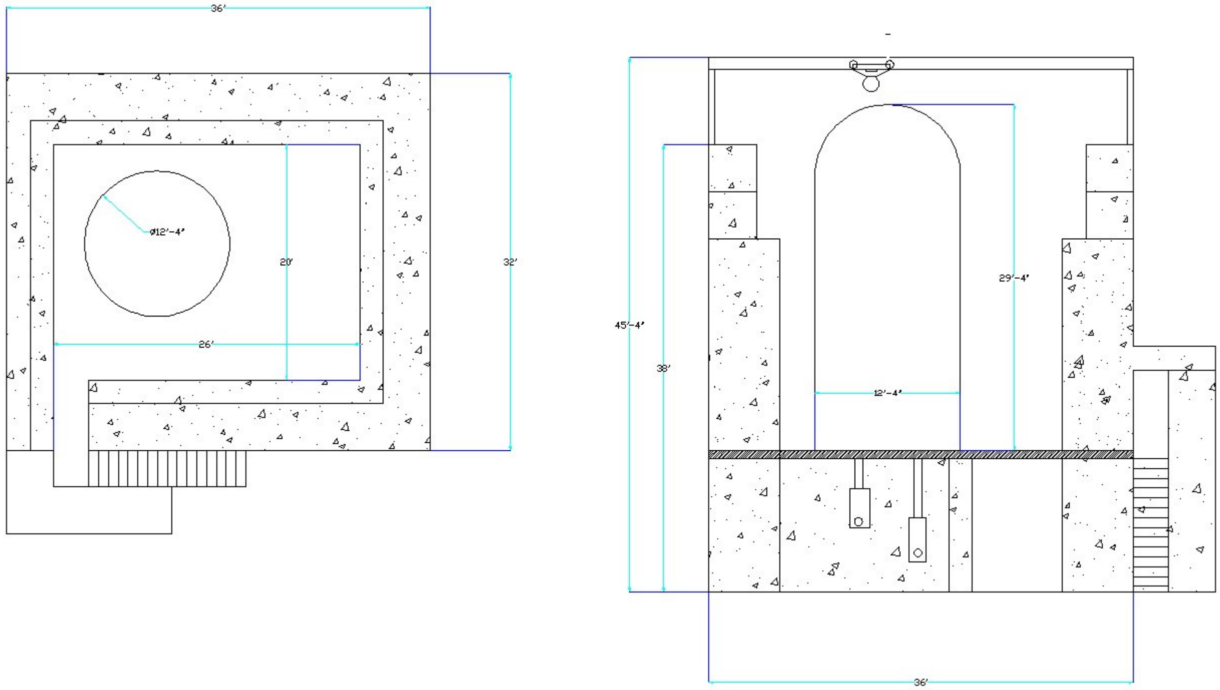

Fig. 6.2 Schematic drawing of blockhouse which will host Pelletron.

7 OUSTANDING ENGINEERING QUESTIONS

Some modification of the Recycler's Pelletron cooler will be needed to address the following issues:

-operation in a wide range of energies
-use of the same electron beam to cool ions in two collider rings
-suppression of recombination
-large ion beam size at low energies

Below is incomplete list of questions which need to be addressed:

1. Can we use Recycler magnets from 90 degree bends? Quality of field at low energies is an issue.
2. Can we use Recycler's feedback system based on NMR or the field is too low for NMR?
3. Is present 180 ("U-turn") degree turn satisfactory for preserving quality of electron beam from one section to another?
4. Design of undulator for recombination suppression.
5. What engineering modifications to present cooling sections are needed to accommodate undulators?
6. Is required vacuum chamber size in cooling section compatible with present design of cooling section with many things located in between vacuum chamber and solenoids? Issue: vacuum chamber needs to be increase due to large ion beam size at low energy which reduces the space to the inner board of the solenoids.

8 OUTSTANDING PHYSICS QUESTIONS

Besides some technical modifications, this will be the first cooler to cool directly beams under collisions. This puts special requirement on control of ion beam profile under cooling. A careful study of interplay of space-charge and beam-beam effects within the hadron beams is needed to understand the limits of cooling applicability.

Below is incomplete list of questions which need to be addressed:

1. Quality of electron beam transport at lowest energy, including turn around of electron beam between cooling section.
2. Estimates of various contributions to angular budget in cooling section in all energy range of interest.
3. Requirement on energy control in both RHIC rings.
4. Requirement of beam alignment in all energy range.
5. Do we need undulators for recombination suppression?
6. Maximum size of electron beam in cooling section? Cooling with large electron beam on center or small beam off-center?
7. Should we use SAM code for simulations, as FNAL did, or we can us PARMELA, for example?

9 MILESTONES

At this moment it is too early to discuss exact dates when Recycler's cooler will be available. These discussions are expected to take place between BNL and FNAL management sometime during 2010. Some possible scenarios of needed time periods are shown below for assuming two different dates of Pelletron availability.

1. (Assuming FNAL Recycler cooler will be available in October 2011, after Tevatron FY11 run):

Preliminary cost estimate of the project –	November 2009
Physics design complete	December 2010
Architectural design & layout	February 2010-February 2011
Electrical design & layout –	June 2010-June 2011
Mechanical design & layout –	June 2010-June 2011
Site preparation –	February 2011- March 2012 (14 month)
Recycler's cooler disassembly and transport	October 2011-February 2012 (5 month)
Electron cooler installation	March 2012 –January 2013 (10 month)
Commissioning	February-June 2013 (5 month)

Available for FY14 RHIC physics run – November 2013.

2. (Assuming Recycler's cooler is available only in October 2012, after Tevatron FY12 run):

Preliminary cost estimate of the project –	November 2009
Physics design complete	December 2010
Architectural design & layout complete –	August 2011
Electrical design & layout complete –	August 2011
Mechanical design & layout complete –	August 2011
Site preparation –	August 2011- December 2012 (17 month)
Recycler's cooler disassembly and transport	October 2012-January 2013 (4 month)
Electron cooler installation	February-September 2013 (8 month)
Commissioning	October-December 2013 (3 month)

Could be still possible to complete in time for FY14 RHIC physics run, provided that more resources are given for installation and commissioning.

10 WORK SCOPE

Below is summary of needed modifications and related work to adopt FNAL Recycler cooler for RHIC. Listed items are the one used in preliminary cost estimate of the project.

Disassembly & Transportation

Disassemble pelletron -labor and travel
Electrical disconnect of equipment & load centers
Rigging services to load
Transportation - 8 loads at 5000$

Site Preparation at BNL

Design & layout – architectural
Design & layout – electrical
Design & layout – mechanical
Prepare site access road & fence
Modify 4:00 wall, install blockhouse
Fabricate & install upper walls & roof
Insulate & seal blockhouse
Fabricate stairs, platforms and lifts
Install service building
Install SF6 tank foundation
Power to load centers
Lights & utility power
Blockhouse & service bldg AC
Compressed air extension

Fire Alarm & sprinklers
Network & communications
Sesmic consulting

Installation

Assemble Pelletron in blockhouse (thru roof)
Place aux. equipment, stairs & platforms
Run tray to cooling section
Power equipment
Hookup Pelletron, e- transport & cooling section
Design & fabricate undulators
Install undulators
Design of magnets for additional bends
Fabricate U bend +6 -90 degree bends
Controls modifications & adaption
Vacuum modifications
Instrumentation modifications
Power supplies for additional magnets
New power supplies (if needed)
Cooling section modifications (stands, etc,)

11 TRANSPORT AND INSTALLATION TOPICS

Pelletron transport

All of the internal components are supported as a free-standing column from the base of the Pelletron. Everything on the inside needs to be removed down to the lowest tank flange. In other words, one can leave most of the components in the lowest of the three sections of the tank. On the elevation drawing, this would be the portion of the tank that is 124" tall. Everything above this has to be removed to separate the sections of the tank. This is how it was transported at Fermilab (over 3 miles distance). There is quite a bit that has to be disassembled.

BNL personal should take part in disassembling process to learn the details.

Pelletron installation

The blockhouse needs to be big enough to house the counterweight structure for the Pelletron service platform and also the staircase to access the Pelletron.

A 15 ton crane is required. The Pelletron outer vessel is made up of (3) sections that weigh 24,000 lbs, 14,500 lbs., and 21,000 lbs. respectively. These are empty weights. At FNAL, the bottom section (21,000 lb) was transported with most of the components still installed.

9' of crane clearance is not required, but 6' is to remove/install the shell through the lid on top. At FNAL, the building at FNAL was made an extra 3' tall so that one could add one more acceleration section (1 MV) if ever wanted to in the future.

The auxiliary equipment that needs to be located with the Pelletron includes the staircase and counterweight structure. The SF6 transfer skid, chiller, and racks could probably be located elsewhere, but this would make some things inconvenient.

The utility requirements are pretty minimal. 16 gpm of water cooling for 24 kW is needed for the Pelletron SF6 recirculation during operation. At FNAL, another 11 gpm for 16 kW of water cooling for the beamline magnets that are underneath the Pelletron were used.

The elevator is not needed.

Planned blockhouse info:

We can use a 150 ton capacity crane to build a blockhouse ~ 36’ x 36’, with 6’ shielding walls, sandwiched between the shielding at the ~12’ level could be steel plate capable of taking the load of the Pelletron. Instead of steel plate we can use Pelletron’s support similar to the one used at FNAL Recycler - it uses 12’ high hollow concrete cylinder with 18’’ wall thickness.

The roof would be removable.

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APPENDIX

In APPENDIX we put together some basic information relevant to Recycler's Electron cooler at FNAL. This information is extracted from published FNAL presentations and reports and is a courtesy of FNAL. It is provided here only for the purpose of easy reference. More details about Recycler cooler can be provided separately (also Refs. [9-18] and references therein).

A.1 FNAL Recycler electron cooler

Figure A.1 shows general layout of Recycler electron cooling system. The DC electron beam is generated by a thermionic cathode gun located in the high-voltage (HV) terminal of the electrostatic (Van de Graff-type) accelerator called Pelletron. The Pelletron was built by National Electrostatic Corporation (NEC) [18]. After the beam is accelerated in Pelletron to 4.3 MeV it is bent into beam transport line and then bent in another plane to bring it into 20 m long cooling section. After cooling section, electron beam is turned around and brought back to Pelletron.

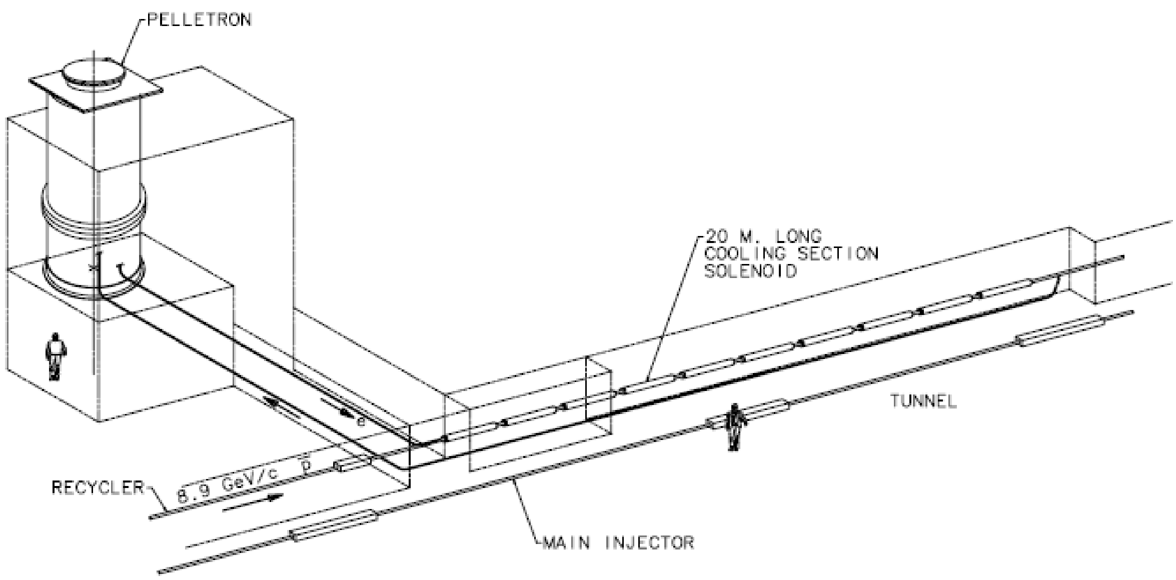

Fig. A.1. Schematic layout of electron cooler in FNAL Recycler.

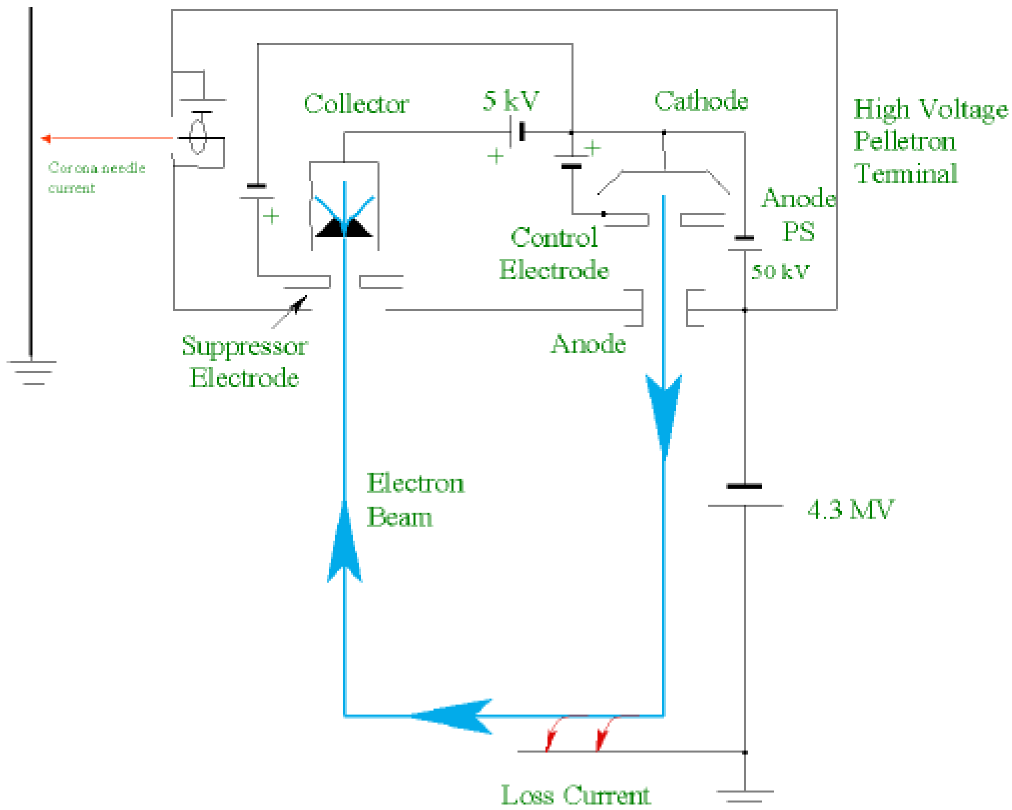

Fig. A.2. Schematics of electron recirculation system.

The electrical schematics of electron recirculation system is given in Fig. A.2. The primary current path is from the cathode at the high voltage terminal potential to the cooling section where the electron beam interacts with the antiproton beam and cooling takes place, then to the collector located in the terminal, and finally through the collector power supply back to the cathode.

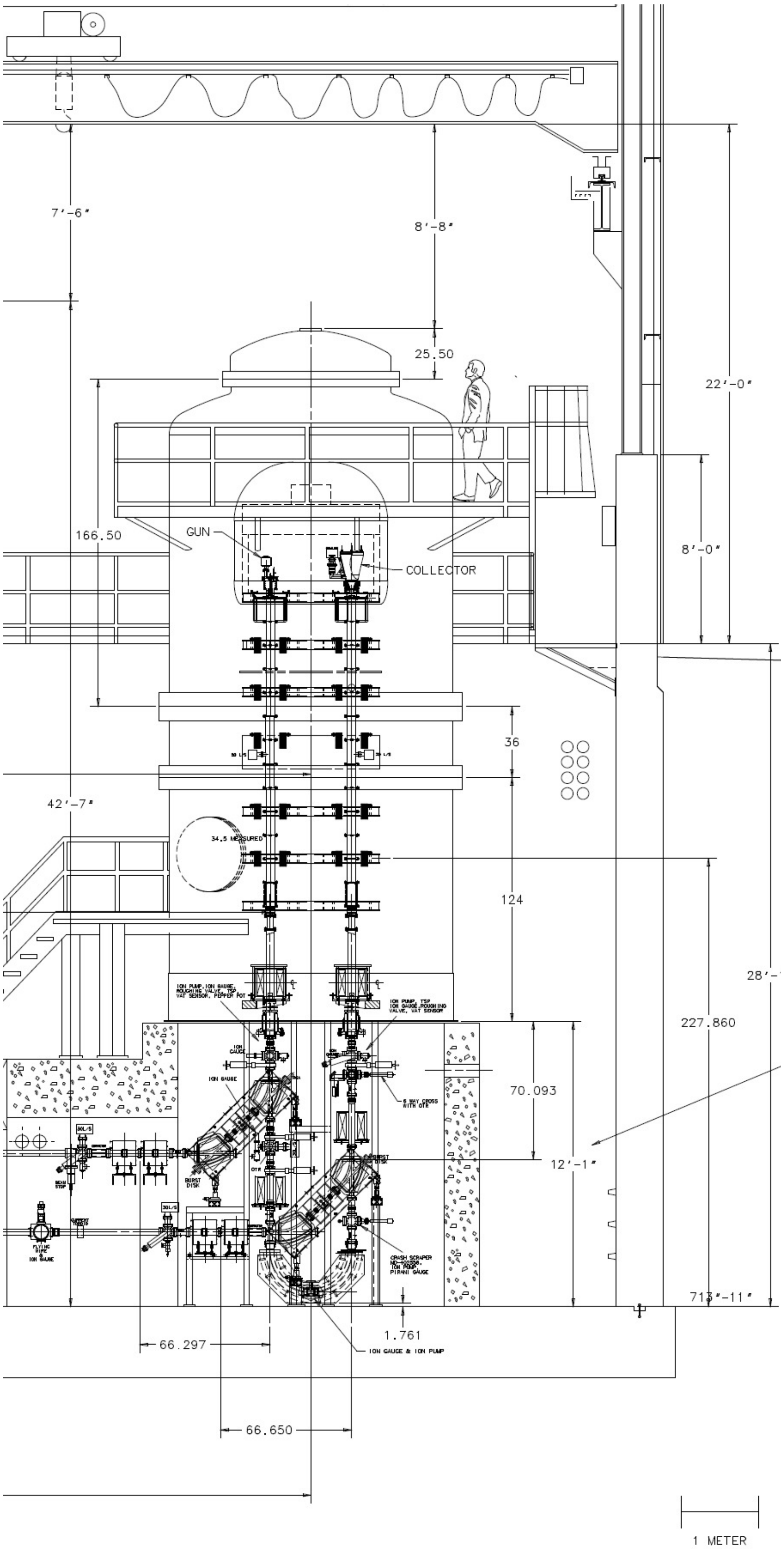

Fig. A.3 FNAL Pelletron dimensions.

A.2 Fermilab's Pelletron

Fermilab bought a commercially-made Pelletron from a company out of Middleton, Wisconsin, National Electrostatics Corporation (NEC) [18]. It is known as the 6URe, a 6 million volt, gas-insulated, electrostatic, single-ended type accelerator, and is designed to accelerate electrons.

There are four major components of the Pelletron: 1) a pressure vessel, 2) a high voltage insulating support structure (the column), 3) a charging system to generate the high potential and 4) evacuated acceleration tubes through which the electron beam passes.

1) The Pelletron is housed in a specially designed and certified steel pressure vessel (the tank) that is 144" in diameter and 326" long. Its purpose is to contain the SF6 insulating gas. The nominal pressure inside the tank is ~70 psi, and nominal temperature is ~31 deg C. The tank has several ports built in: an access port on the lower end to allow servicing of components inside; SF6 drain ports; ports for the generating voltmeter (GVM), capacitive pick-off (CPO) and service platform support cables; and ports for electrical feedthrus, beam tubes, and safety sensors.

The SF6 recirculation system is at the base of the tank and serves four functions: cooling, drying, filtering, and removing breakdown products of the SF6. A recirculation blower pulls the warm SF6 gas into the cooling skid located on the platform where the gas is cooled, dried and filtered before returning it to the tank. For servicing the Pelletron, the SF6 gas is removed from the tank to an outside vessel by a transfer skid located on the floor just outside the cave area in MI-31.

2) The support column is a set of hollow aluminum disks, so-called separation boxes, supported by 6 insulating posts. Each post is an assembly of metal and ceramic disks bonded together. In addition to providing mechanical support for all elements, the posts are used to hold electrostatic guarding rings (hoops), which cover the inner space of the column and provide an even distribution of electric fields. The voltage between hoops is distributed by a chain of resistors mounted at one of the posts.

The separation boxes contain electrical generators, powered by a rotating shaft; power supplies of lenses and correctors; and controlling electronics. A larger separation box in the middle of the Pelletron (#3) also has two ion pumps with their power supplies.

3) The high voltage terminal is mounted at the top of the column. It houses the terminal charging system, electron gun, collector, and electronics. A cylindrical shell, or dome, surrounds the terminal structure. Electrical power for the terminal is supplied by a drive shaft system consisting of a motor mounted on the base bulkhead plate to drive alternators in the terminal via an insulating shaft. High voltage is generated by means of a mechanical charging system (the chain) consisting of steel pellets (from which the name "Pelletron" comes from) connected by nylon insulating links rotating around two pulleys, one at the ground end driven by an electric motor, and one in the HV terminal. A 7.5 horsepower motor in the bottom of the tank provides power to turn drive sheaves of the chain.

Negative charge is induced on the pellets at the ground end and carried by the pellets to the HV terminal; positive charge is induced on the pellets in the terminal and carried to ground for a total charging capacity of more than 300ua.

The terminal voltage control system is a closed loop voltage control system. The device which accomplishes this is known as the Terminal Potential Stabilizer (TPS). There are several devices that are used as inputs for the TPS:

The Generating Volt Meter (GVM) is a precision device which generates a signal proportional to the voltage on the accelerator terminal. It is located on the inside wall of the tank and consists of a motor which turns a rotating vane in front of 8 static sector plates. When voltage is applied to the accelerator terminal an AC voltage is induced on the plates. This signal is amplified, rectified, and read out on a digital display on the TPS.

The Capacitive Pick-Off (CPO) is used to detect high frequency changes in the terminal potential. The CPO plate is located on the inside wall of the tank, read out using a scope.

Terminal voltage is stabilized by a corona current flowing from needles located in the terminal shell (the so-called Corona Probe). This current is a function of the needle potential with respect to the terminal surface around it. To control the terminal voltage, the needle is connected to a high voltage triode. Correction signal, proportional to the difference between GVM reading and the voltage set by R:TPSTRV is applied to the triode grid. This in turn regulates the current drawn from the terminal by the corona probe.

4) Two identical tube assemblies are located in the column: the acceleration tube transports the injected negative electrons from the terminal to ground; the deceleration tube transports the electrons back from ground to the terminal collector. There are six sections in each tube. Ends of each section are connected electrically and mechanically to separation boxes. Sections are composed of 1' long modules, which consists of a bonded set of ceramic cylinders and titanium disks with bonded titanium vacuum flanges at the ends. The standard module has 21 insulating gaps with voltage distributed along the module by a string of 0.5 Gohm resistors. Electrodes attached to the titanium disks determine the electrostatic fields in vacuum; the minimum aperture in the tube is 1".

A.3 Recycler cooler devices

The Electron Cooling beam line is made up of several distinctly-named sections. The electron beam first enters the A*cceleration line* which runs from the gun through the bottom of the tank and ends before the beam enters the first 90 degree dipole bend magnet (R:DYS1A) under the tank. (The 90 degree dipole bend magnets are made up of two 45 degree bend magnets, labeled A and B.)

The *Supply line* runs from the first 90 degree dipole bend magnet (R:DYS1A) located under the tank, goes through the MI-31 Stub area and ends at the next 90 degree dipole bend magnet (R:DXS6B) located in the Main Injector Tunnel. The ECool beam line merges with the Recycler beam pipe near the location R:H307.

In the short Adjustment (Before Cooling) line, located in the Main Injector tunnel, electrons are focused and steered to provide a parallel beam in the cooling section. This line is between the 90 degree dipole bend magnet R:DXS6B and the first cooling section solenoid.

The 20 meter long *Cooling Section* is located in the Main Injector tunnel and is composed of 10 identical solenoid modules.

The *180 degree bend region* is located in the Main Injector tunnel and runs from the end of the Cooling Section to just after the 180 degree dipole bend magnet R:DYQ3B. The 180 degree dipole bend magnet consists of two 90 degree dipole bend magnets: R:DYQ3A and R:DYQ3B; the ECool and Recycler vacuum pipes are separated inside the magnet R:DYQ3A near location R:V305.

The *Return line* is located in the Main Injector tunnel and begins right after the180 degree dipole bend magnet (R:DYQ3B) and ends at the next 90 degree dipole bend magnet (R:DXT1A). The Return line is between the Recycler and Main Injector, so is very vulnerable to Main Injector losses and ramp cycles.

The *Transfer line* begins in the Main Injector with the 90 degree dipole bend magnet (R:DXT1A), goes through the MI-31 stub area and ends under the tank at the last 90 degree dipole bend magnet (R:DYT6B).

The *Deceleration line* begins under the tank in MI-31 after the last 90 degree dipole bend magnet (R:DYT6B) and ends inside the tank at the collector.

There are two operating modes for the Electron beam line. When the electron beam starts at the gun, passes through all of the separate sections and returns to the collector, this is called **Full Line mode**. In the second mode, called **U-Bend mode,** the electron beam begins at the gun, travels through the Acceleration line, but instead of being bent into the Supply line, the first 90 degree dipole bend magnet (R:DYS1A & B) is turned off and the beam goes straight towards the ground until it reaches the 180 degree dipole magnet known as the U-Bend magnet. After passing through the U-Bend magnet, the beam returns to the Deceleration line and ends in the collector. The major difference between the two modes is that for Full Line mode the Main Injector Safety System must be enabled. In U-Bend mode, the electron beam never leaves MI-31, so this mode can be run regardless of the status of the Main Injector. To switch from full line mode to U-Bend mode, a key must be turned on the interlock chassis at MI-31.

The naming convention used by ECool is different than the other beam lines in the Accelerator Div. The naming of the devices is based on the positions of the solenoids. The naming begins with a solenoid and everything after it is based on that solenoid until another solenoid is reached. As an example, in the Acceleration line, the first solenoid outside the tank is R:SPA06. Every device after that will be R:xxA06x until you get to the solenoid R:SPA07. After that the devices will be R:xxA07x until you get to the U-Bend magnet. This is generally true throughout the ECool beam line. The names given to the devices are based on what type of device it is.

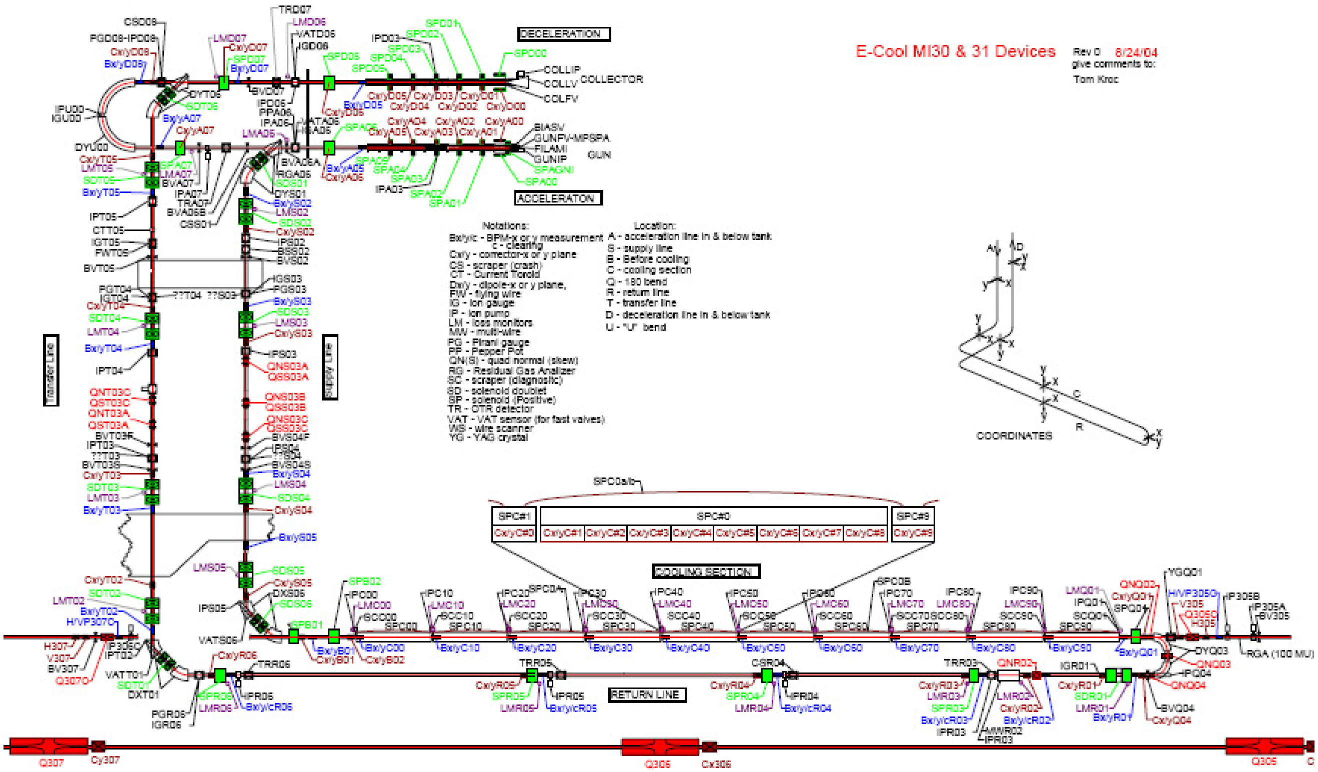

Fig. A4. Recycler cooler devices.

Device name	Quantity
BPM's	2x31
CS (scraper, crash)	2
Cx,y (correctors)	248
SC (scraper, diagnostic)	11
Dx,y (dipoles)	12
FW (flying wire)	1
IG (ion gauge)	9
IP (ion pump)	34
LM (loss monitor)	31
MW (multi wire)	1
PG (Pironi gauge)	4
PP (pepper pot)	1
QN (quad)	14
RG (residual gas analyzer)	1
SD (solenoid doublet)	12
SP (solenoid positive)	20
TR (OTR detectors), YAG crystal	1,1
VAT (valve, fast sensor)	3
WS (wire scanner)	0

A.4 Recycler cooler diagnostics

Implementation of electron cooling requires several diagnostic devices to align and characterize the ion and electron beams. Across the cooling section, an angular precision of 10-4 between the two beams and the solenoid field is needed. The beam centers need to be determined to a few tenths of a millimeter with beams of about one centimeter diameter. Reasoning for diagnostic devices which are being used in Recycler cooler can be found in Ref. [14].

BPM's

The BPM system used by ECool is a very unique system. It was essential to have a system that would very accurately measure the relative position of the electron and Pbar beams to within +/- 100μm of each other in the cooling section. In order to separate the signals from each beam, the electron beam is modulated at a frequency of 32 kHz. The digital signal receiver (DSR) processing electronics has the ability to discriminate between different signal frequencies by down-converting an input frequency to base band using a numerically controlled oscillator. The circulating Pbar beam is detected at the revolution frequency and the electron beam is detected at 32 kHz.

The operational BPM system located at MI-31 consists of two VXI crates.

There are four beam position measurement modes:

1. Electron beam position measurement mode;
2. Circulating beam position measurement mode (for measuring Pbars);
3. Switched beam position measurement mode (Both);
4. Electron pulsed beam position measurement mode.

The user can invoke any of the above modes from the DATA DISPLAY sub-window. Within this sub-window there are two pop-up menus: BEAM and DATA. The BEAM menu selects the beam type to measure; electron, circulating Pbars, or both, which corresponds to Switched beam position measurement mode. Electron pulsed beam mode will be discussed later. The DATA menu option, SLOW/HiRes or FAST/LoRes, selects the filtering to apply to the position data. The SLOW position data is generated from a narrow band filter (BW < 5 Hz), and is an averaged output of the FAST positions; this reduces the noise in the position data, relative to the FAST position data, at the expense of a longer response time. The user can change the tuning frequency for the corresponding measurement from the TIMING sub-window. In general, the tuning frequency is not necessarily the same as the modulation frequency. The user can move the tuning frequency off the modulation frequency to avoid saturation in the DSR modules. A common indicator of saturation is high beam intensity and unstable fluctuation of beam position measurements. During normal cooling operation, this frequency is automatically set. These timers should not be changed without expert approval.

While in the electron or circular measurements mode, the ECool BPMs provide horizontal and vertical positions for either electrons or circulating Pbars. The timing of the measurement is controlled by the TCLOCK event $EB. This event can be tied to other TCLK events and delayed from these events by a specified amount using the device R:ECDLY, thus allowing the user to accurately time data collection relative to other accelerator events. Once the $EB event is received, the front end collects data from the DSPs for all BPMs and maps that to the ACNET BPM display program (E50). In the switch mode, the BPMs alternate between measuring beam position for both beams. The frequency with which the measurement alternates between electron and circulating Pbars can be changed from the TIMING sub-window.

Once the measurement type, BEAM and DATA has been set, a click of SNAPSHOT in the DISPLAY DATA window invokes the corresponding measurement mode. The selected mode remains until the user selects another mode. The message window will display the progress of the operation, as well as any errors encountered. Messages from different sources appear in the message window with different colors; messages from the ECOOLBPM system will appear in yellow. The instantaneous beam positions measured for all BPMs in the system will be shown in a new pop-up window. Continuous beam positions are also available as ACNET devices, which can also be shown on fast time plots. The ranges of operational BPM intensities large enough to give reliable position information are as follows: for DC beam in either Electron or Circular mode need to have a BPM intensity of at least 150; for pulsed beam in pulsed operating mode need to have a BPM intensity of at least 10.

The electron pulsed measurement mode can be invoked by clicking on PULSE. There is a time delay between the electron pulse TClock event trigger and data acquisition due to the digital signal processing. The data acquisition is triggered by the TCLCK event $EB. It is important to check the status of the ECool Variable Pulse Delay ACNET device – R:ECDLY. This device should be on. When R:ECDLY is off, a red asterisk will be shown next to it on an ACNET parameter page.

OTR's

Optical transition radiation monitors are being used to image the transverse profiles of the 4.3 MeV electron beam used in the electron cooler at Fermilab. The linear response of OTR monitors to beam charge, the high spatial resolution and the fact that the radiation is prompt has several advantages over more traditional imaging devices. The transition radiation is produced by the charged particles as they traverse the boundary between media with different dielectric constants, for example a metallic or dielectric foil in vacuum. For relativistic electron beams, transition radiation can be measured at optical wavelengths (OTR) with readily available equipment and imaging techniques. The imaging system used in the FNAL set-up consists of digital CCD cameras connected to computers via IEEE 1394 fire-wire interfaces. This provides the operator with real-time beam images and tools for image analysis and measurements of the beam's dynamic properties as a function of the optics of the accelerator. The OTR diagnostic systems used at the cooler are designed to be routinely used to optimize the beam transport and to measure the transverse beam size and shape with a resolution down to 25 μm. Very thin (5 μm) Aluminum foils are being used to reduce the background signal due to beam scattering and bremsstrahlung radiation.

Other diagnostic include:

Scrapers
Flying wire
Loss monitors
Pepper pot
YAG
Multiwire

A.5 Control system

The control system used by the Pelletron came with it from NEC and is called AccelNet. AccelNet stands for 'Accelerator Network control system' and is designed specifically for the control of electrostatic particle accelerator systems. AccelNet runs on PC hardware under the Linux operating system.

There is a dedicated PC located in rack 103 in the MI-31 control room that runs the Pelletron AccelNet control system. Accelnet controls everything inside the tank. The readbacks come out of the Pelletron tank via a fiber optic light link and go into the Pelletron CAMAC crate located in rack 216 in MI-31. They are then accessed through the AccelNet PC. These readbacks are also interfaced with the Accelerator Division CAMAC system through a VME front end node called 'ECOOL' (located in the computer room across from the Main Control Room). Through node ECOOL, the readbacks from inside the Pelletron tank can be viewed and controlled via ACNET parameter pages. It should be noted that when the shaft is off, there is no power going into the Pelletron tank, thus no readbacks coming out. If either the AccelNet PC or node ECool develop a problem (i.e. hang-up, crash, etc.), readbacks will stop updating or will report back errors on parameter pages. If this happens, the ECool on-call person should be contacted. If the problem is with node ECool, a simple reboot may solve the problem. But if the problem is with the AccelNet PC, it is more complicated since problems with the PC can cause secondary problems with node ECool.

Readbacks for all other devices associated with the ECool beam lines, diagnostics, etc. come through Acceleration Division controls VMEs and IRMs located in MI-31.

A.6 Recycler cooling section.

The cooling section is comprised of ten identical 2-meter long solenoid modules. Each module consists of a solenoid with end coil and dipoles correctors, a vacuum system, magnetic shielding, and support system.

Parameter	Value
Total length of the cooling section	20 m
Number of modules	10
Gap length	8 cm
Maximal magnetic field	200 G
Module Solenoid	
Length	188.2 cm
Inner tube ID	14 cm
Outer tube OD	20 cm
Magnetic field at 1 A	40 G
Trim solenoid	
Length	3.5 cm
Inner tube ID	14 cm
Outer tube OD	20 cm
Magnetic field at 1 A	49 G
Main dipole corrector	
Length	23.3 cm
Maximum current per coil	1 A
Maximum field	0.8 G
Material	2-ounce copper on Kapton
Trim dipole corrector	
Length	3.5 cm
Maximum current per coil	1 A
Maximum field	1 G
Material	2-ounce copper on Kapton
Shielding	
Material thickness	1 mm
Magnetic permiability at 0-field strength	$4 \cdot 10^4$
number of shielding layers	3
Material	Permalloy 80

Table: Parameters of Recycler electron cooling section.

A.7 Utilities

Vacuum System

The ECool vacuum system is the same system that is used throughout the Main Injector with the exception of the fast acting valve system. All of the readings come through a VME node called ECVAC, located in relay rack 202 in MI-31. This rack also contains the vacuum CIA crate and the ion gauge power supplies. Rack 201 contains all of the ion pump power supplies.

Inside the tank, the vacuum is kept at roughly 10^{-9} Torr. There are ion pumps located on the gun, at deck level 3, and on the collector. There are also manual vacuum valves located under the tank at locations A06, A07, and D07. When there is a full discharge of the high voltage inside the tank, the vacuum will rise very rapidly. It can reach as high as 10^{-5} Torr. When this occurs, the electron beam cannot be run until the vacuum recovers. The recovery will take anywhere from 15 minutes to hours, depending on how bad the voltage discharge was. If the vacuum pressure rises too high, the fast acting valve system will close the valves connecting the Ecool beamline with the Recycler.

In the beamline sections, vacuum is kept roughly at10^{-10} Torr. There are ion pumps at every solenoid location. There are manual vacuum valves located at the following locations: S02, Q04, and T05.

The Pelletron uses sulfur hexafluoride (SF6) inside the tank because of its properties as an electrical insulator. The SF6 is pressurized to ~75 psig. A system of fast acting beam valves has been installed in the event of a catastrophic vacuum failure that would cause the SF6 to flood the beam pipe and possibly contaminate the Recycler. In the event of such a failure, the SF6 would reach the Recycler beam pipe and contaminate the entire Recycler vacuum system in just over 5 seconds. The fast acting valve system also protects the Recycler vacuum system against high pressure vacuum bursts resulting from full discharges in the Pelletron that could rupture vacuum components.

Two fast-acting valves are located on the MI-31 side and two on the Recycler side. The function of the first set of valves, one in the Supply line and one in the Transfer line, is to minimize the amount of SF6 gas that will reach the Recycler. The second set of fast valves, located on either side of the cooling section in the Recycler, will stop the flow of gas from reaching the rest of the Recycler vacuum system. The fast valves are activated by what are known as VAT controllers, which are triggered by the VAT cold cathode gauges when a pressure of 5×10^{-4} Torr is reached. The valves will close in 32 ms. The valves on the MI-31 side (BVS04F and BVT03F) are controlled by the cold cathode gauges and controllers on that side. The Recycler fast valves (BV304F and BV308F) are controlled by the gauges and controllers on the Recycler side. A trip on the MI-31 side will not affect the Recycler valves. Likewise, the Recycler fast valves will both close if either VAT gauge on the 90 degree bend magnets in the Recycler read greater than 5×10^{-4} Torr.

The four fast acting valves are not completely leak tight. Thus, each one is backed by a standard pneumatic valve, which is activated through the CIA crate vacuum interlocks. They take a few seconds to close. These valves will close if three or more of the four selected ion pumps on either side of the valve trip off. In the MI tunnel, these valves are named BV304S and BV308S. In MI-31 they are BVS04S and BVT03S. The ion pump permits will close the fast and slow valves. To get the permits back, first a reset and on command must be given to the slow valves, then to the fast valves.

Two vacuum burst disks are located on the 90 degree bend magnets under the Pelletron. In the event of vacuum system over-pressurization, the disks will rupture, relieving the pressure in the system.

Water cooling system

The Pelletron uses three different water systems for cooling.

The first is the cooling water skid located in MI-31 next to the elevator mechanical room. This water cooling skid is a closed loop system that was originally filled with LCW from the Main Injector system. If it needs LCW added, it would be taken from the MI system. This skid utilizes a Freon heat exchanger that is located behind the MI-31 building inside the fenced area. This fenced area is classified as a High Radiation Area when the Pelletron is running and RSO approval is needed to access it. There are only a few devices that are cooled from this skid. They are split between two systems, the Silo magnet water system and the SF6 Heat Exchanger water skid.

The Silo magnet water system cools:
-The U-Bend magnet under the Pelletron tank and its associated power supply, located under the stairs next to the MCC;
- The solenoid doublets SDS01 and SDT06 inside the two 90 degree dipole bend magnets located under the tank (the dipole magnets themselves are air-cooled);
- Two of the four Walker solenoid magnets SPA07 and SPD07 (the other two Walker solenoids, SPA06 and SPD06 are inside the tank and are SF6 cooled).

The SF6 Heat exchanger water skid cools:

- The SF6 recirculation skid exchanger located on the platform next to the Pelletron tank.

The second water system used by ECool is called the Collector Cooling system. It is located inside the Pelletron tank on top of the collector, and is used to cool the collector. It is a closed loop system that uses deionized (DI) water. To fill this system, the Pelletron tank must be accessed, so the SF6 would have to be transferred to the holding tank outside. The device that monitors this is R:COLFLO. It should be noted that when the rotating shaft is off, there will be no readbacks for this device, so one can only tell if this system has a problem when the shaft is running.

The third water system used by ECool is the Main Injector LCW system. This is used to cool the solenoids in the cooling section. There are 10 solenoids in the cooling section that use MI LCW. Their temperatures are monitored by thermocouples named R:TCC00, TCC10, TCC20, and so on to TCC90.

A.8 Some aspects of Recycler cooler operation

Current losses:
Current losses have to be low. Losses to the tube electrodes should not exceed few μA to avoid overvoltage. Losses at the ground should not exceed few tens of μA to avoid damaging the vacuum chamber.
Cooling section:
Low magnetic field in cooling section. A typical length of perturbation is 20cm which is
much shorter than electron Larmor length.
Recirculation stability:
ECool protection system closes the gun if the Pelletron voltage decreases by more than 5kV or the signal of radiation monitor exceeds a threshold.
Machine protection system:
During energy recovery process in Pelletron losses are kept below 10 μA. Increased beam loss during this process can lead to a reduction of the terminal voltage and, in turn, an interruption in recirculation.

Fast protection circuitry has been developed at the terminal level as part of a Machine Protection System (MPS) which closes the gun in 1 μs if the terminal voltage decreases because of higher losses [13].